

Rates of Diffusion of Copper and Zinc in Alpha Brass



By Ernest Kirkendall

Lars Thomassen

Clair Upthegrove

1939



DISCUSSION OF THIS PAPER IS INVITED. It should preferably be presented by the contributor in person at the Detroit Meeting, October, 1938, when an abstract of the paper will be read. If this is impossible, discussion in writing (2 copies) may be sent to the Secretary, American Institute of Mining and Metallurgical Engineers, 29 West 39th Street, New York, N. Y. Unless special arrangement is made, discussion of this paper will close Jan. 1, 1939. Any discussion offered thereafter should preferably be in the form of a new paper.

Rates of Diffusion of Copper and Zinc in Alpha Brass

BY ERNEST KIRKENDALL,* JUNIOR MEMBER A.I.M.E., LARS THOMASSEN,† AND
CLAIR UPTHEGROVE,‡ MEMBER A.I.M.E.

(Detroit Meeting, October, 1938)

THE amount of research done in the last few years on the subject of diffusion in solid metals is significant of the importance of this problem. To review the literature dealing with diffusion is unnecessary here. Desch¹ in 1912 reviewed the work that had been done on diffusion in solids and gave a bibliography of the literature published before that time. Mehl's paper in 1936² is an excellent review of diffusion in metals and contains a large bibliography. Of importance also for its review and bibliography is an article by A. I. Krynitsky.³

While considerable material has appeared in the literature on diffusion in brass, the amount of information is not great compared to that pertaining to some of the other alloys. Most of the information published is of a qualitative nature; that which is quantitative varies considerably. Thus the quantitative determination of the rates of diffusion of copper and zinc in alpha brass by a new method appeared worth while.

In the present investigation the rate of diffusion of zinc in approximately the same composition alpha brass has been determined at three temperatures.

PROCEDURE

The method used consisted of plating copper on a beta brass, heating it to allow diffusion to take place, and measuring the concentration of copper by determining the lattice constant of the alloy. This method is unique in that it uses a beta brass of such a composition that at the temperature at which diffusion takes place the beta brass is saturated with copper. Thus, while the beta brass supplies the zinc, no diffusion takes

This paper is based on a dissertation presented by Ernest Kirkendall to the faculty of the Horace H. Rackham School of Graduate Studies at the University of Michigan in partial fulfillment of the requirements for the Degree of Doctor of Science. Manuscript received at the office of the Institute June 1, 1938.

* Instructor of Chemical Engineering, Wayne University, Detroit, Mich.

† Associate Professor of Metallurgical Engineering, University of Michigan, Ann Arbor, Mich.

‡ Professor of Metallurgical Engineering, University of Michigan.

¹ References are at the end of the paper.

place in the beta brass. As fast as zinc is taken from the beta brass, the beta brass changes to alpha brass and all of the diffusion takes place in one phase. Table 1 gives the compositions of the various brasses used.

TABLE 1.—*Brass Analyses*

Brass	Per Cent Zinc	Temperature at Which Used, Deg. C.
A	56.41	600
B	57.52	655
C	58.63	720

Ingots of the compositions given were cast, using zinc of 99.99 per cent purity and copper 99.94 per cent. These were then rolled and annealed in several stages to produce a chemically homogeneous strip $\frac{1}{8}$ in. thick. These strips were cut into 4-in. lengths, machined and two surfaces

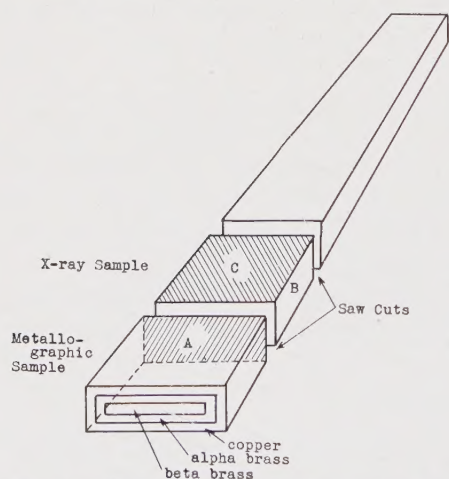


FIG. 1.—SHOWING LOCATION OF SURFACES TO BE EXAMINED ON PLATED BRASS BAR.

Surface A is to be exposed when the metallographic sample is mounted in Bakelite. Side B and the opposite side are to be ground down to the beta brass before the X-ray sample is mounted in Bakelite with surface C exposed.

3° C. At the end of the prescribed time for diffusion, the bar was removed from the furnace and quenched in water. After heating, the flat sides, of which surface C (Fig. 1) is a part, were polished to insure their being flat. Two pieces $\frac{3}{8}$ in. long were then carefully cut from the bar, and the bar returned to the furnace for further diffusion.

The first sample was mounted in Bakelite with surface A (Fig. 1) exposed. This provided a cross section for the photomicrographs.

polished until parallel to within less than one half of one thousandth of one inch. Copper was electroplated onto these strips to a depth of about 0.010 in. on each surface, and the bars were heated under vacuum at 450° C. for a few hours, to remove any occluded hydrogen.

The degassed copperplated brass bars were now ready for the actual diffusion treatment. A sample $\frac{3}{8}$ in. long was cut from one end of each bar, polished, etched and photographed to show the original stock before the diffusion treatment (Fig. 2). The bar was then heated for the prescribed times at the desired temperatures in an electric muffle furnace. The temperatures were controlled to within plus or minus

The second sample was mounted in Bakelite so that surface *C* was exposed. The second sample was to be used for the X-ray pictures.

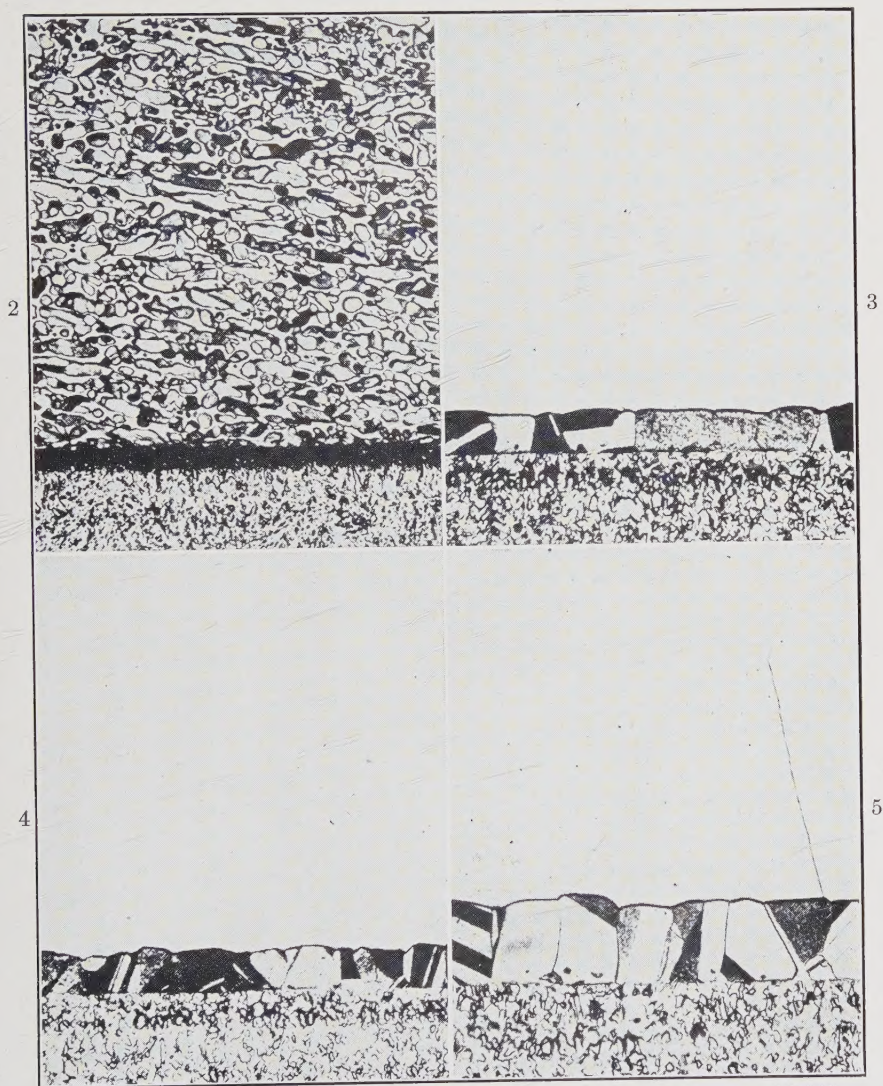


FIG. 2.—B SERIES, ANNEALED STOCK BEFORE DIFFUSION TREATMENT. $\times 200$.
 FIG. 3.—B SERIES, HEATED 1 HOUR AT 655°C . AND QUENCHED. $\times 200$.
 FIG. 4.—B SERIES, HEATED 1 HOUR AT 655°C . AND QUENCHED. $\times 200$.
 FIG. 5.—B SERIES, HEATED 4 HOURS AT 655°C . AND QUENCHED. $\times 200$.

During the heating operation described above, some of the beta brass and some of the copper become alpha brass. This produces a layer of alpha brass, bounded on one side by beta brass and on the other side by pure copper. The alpha brass layer was uniform enough to permit

several X-ray back-reflection pictures to be taken at different depths and thus determine the concentration gradient. The amount of metal diffusing across the original interface was measured by determining the

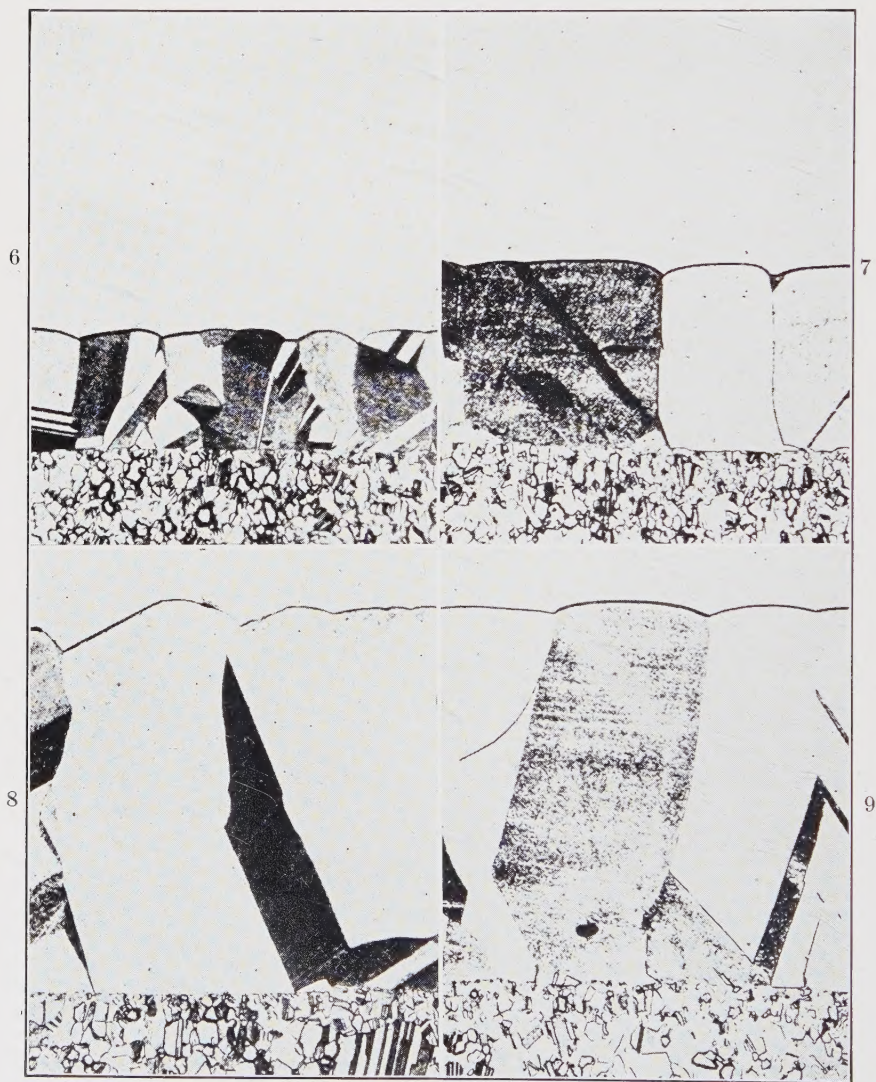


FIG. 6.—B SERIES, HEATED 10 HOURS AT 655° C. AND QUENCHED. $\times 200$.
 FIG. 7.—B SERIES, HEATED 24 HOURS AT 655° C. AND QUENCHED. $\times 200$.
 FIG. 8.—B SERIES, HEATED 96 HOURS AT 655° C. AND QUENCHED. $\times 200$.
 FIG. 9.—B SERIES, HEATED 96 HOURS AT 655° C. AND QUENCHED. $\times 200$.

depth of the alpha layer metallographically and obtaining from the X-ray data the composition of the alpha phase from the original to the final alpha-beta interface.

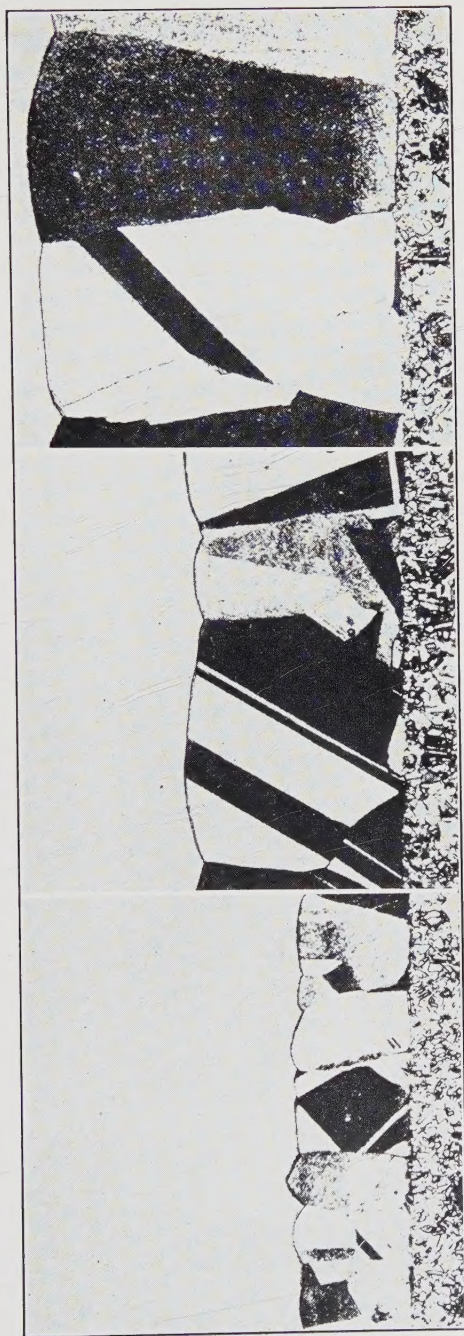


Fig. 12.

Fig. 11.

Fig. 10.

FIG. 10.—A SERIES, HEATED 24 HOURS AT 600° C. AND QUENCHED. $\times 200$.
 FIG. 11.—A SERIES, HEATED 96 HOURS AT 600° C. AND QUENCHED. $\times 200$.
 FIG. 12.—A SERIES, HEATED 339 HOURS AT 600° C. AND QUENCHED. $\times 200$.

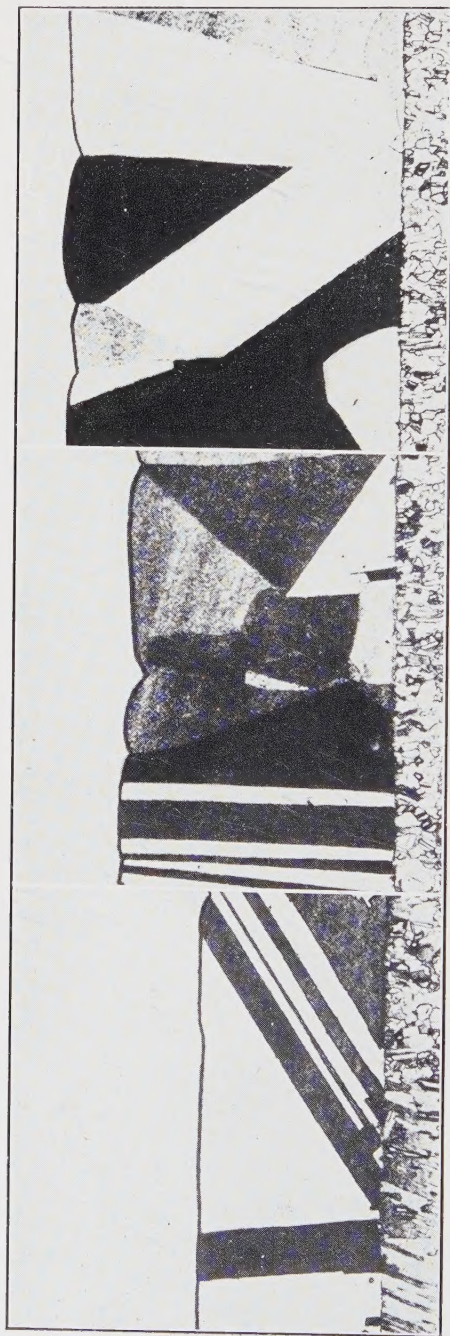


Fig. 13.

Fig. 14.

Fig. 15.

FIG. 13.—C SERIES, HEATED 8 HOURS AT 720° C. AND QUENCHED. $\times 200$.
 FIG. 14.—C SERIES, HEATED 16 HOURS AT 720° C. AND QUENCHED. $\times 200$.
 FIG. 15.—C SERIES, HEATED 24 HOURS AT 720° C. AND QUENCHED. $\times 200$.

The X-ray sample was polished to the desired depth, that is about one half of one thousandth of one inch less than the location of the desired back-reflection picture. The remainder of the metal was removed by etching in a 25 per cent aqueous solution of nitric acid. X-ray pictures were taken, each 0.001 to 0.003 in., depending upon the sample. From the location of the lines appearing on the X-ray film, it was possible to calculate the lattice constant for the brass at the depth examined. From the lattice constant it was possible to calculate the composition of the alpha brass at each of the layers examined.

The X-ray tube used was a gas tube with a cobalt target. The sample was placed in the center of the camera and rotated by a small motor in a plane perpendicular to the X-ray beam during the exposure. Carefully reduced gold powder was sprinkled as a thin layer on each sample to act as a reference substance. This made it unnecessary to know accurately the film-to-sample distance and has been shown to give very accurate results.

RESULTS

Figs. 2 through 15 show the photomicrographs of the samples at 200 diameters. The first eight photomicrographs show all of the samples for the B series. The remaining six show the three more important samples of each of the other series. An alpha brass layer is formed on each side of the original interface. The alpha layer inside of the original interface is composed of large columnar grains with a definite final interface caused by the change in phase. The higher copper alpha brass layer outside the

TABLE 2.—*Effect of Time and Temperature on Diffusion*

Sample No.	Temperature, Deg. C.	Time, Hr.	Penetration, ^a In.
A2	600	2	0.0009
A3	600	9	0.0018
A4	600	24	0.0030
A5	600	96	0.0054
A6	600	339	0.0094
B2	655	1	0.0010
B3	655	4	0.0021
B4	655	10	0.0030
B5	655	24	0.0048
B6	655	96	0.0098
C2	720	1	0.0016
C3	720	3	0.0028
C4	720	8	0.0048
C5	720	16	0.0069
C6	720	24	0.0086

^a Penetration was measured as the distance between the original interface and the final alpha-beta interface.

original interface shows no change in grain shape nor a definite final interface, since copper and alpha brass have the same atomic arrangement. Fig. 2 shows the degassed stock for series B just before the diffusion treatment. This sample after cooling slowly has an alpha plus beta core surrounded by the copperplate. Figs. 3 and 4 as well as 8 and 9 are

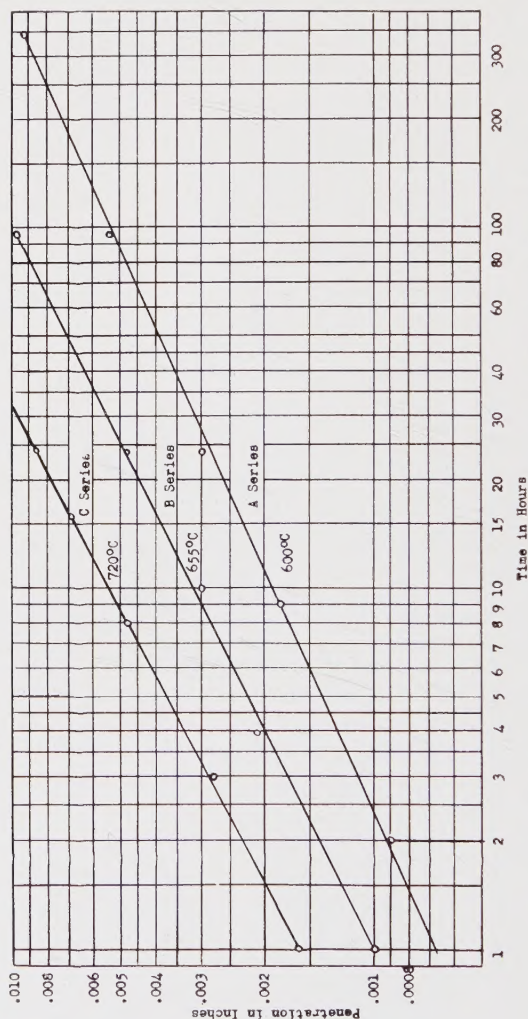


FIG. 16.—EFFECT OF TIME AND TEMPERATURE ON DIFFUSION IN ALPHA BRASS.

duplicates as far as measurements are concerned. Taken at different positions on the same sample, these show that the alpha layer formed between the original and final interface is uniform in depth.

Since the original and final alpha-beta interfaces are definite, all calculations are based on the diffusion of copper into this layer. An equal number of atoms of zinc must diffuse out of this layer to produce a higher

copper alpha layer just outside the original interface, but its outer boundary is not definite microscopically. The side showing the new interface is used because in determining the amount of metal diffusing only the change on one side of the original interface need be known. Table 2 gives the distance between the original and final interfaces for each sample. These data are shown on a log-log plot of time versus temperature in Fig. 16. Three straight lines are produced.

The quantitative treatment of diffusion in solid metals is based on Fick's law:

$$dm = -DA(dc/dx)dt \quad [1]$$

where dm is the amount of matter diffusing in time dt in the direction of a concentration gradient $-dc/dx$ and across an area A . D is the diffusion coefficient. Thus D represents the number of grams of material diffusing across an area of one square centimeter in one second and in the direction of a concentration gradient of one gram per cubic centimeter per centimeter. D is constant only if the temperature and composition remain constant. A change in phase causes D to change abruptly and a change of concentration within a phase produces a corresponding change in D .

In computing rates of diffusion, it is necessary to know the concentration gradient at the point where the diffusion rate is being measured as well as the amount of metal transferred. Both of these factors can be obtained by determining the composition of the brass at various locations by means of X-ray pictures. The results obtained are given in Tables 3, 4 and 5.

Plotting the X-ray data showing the variation in zinc content at various depths, a graph similar to Fig. 17 is obtained. When the distance between the original and final interfaces was divided into 10 equal

TABLE 3.—X-ray Data for Master Curve for Series A

Sample No.	Total Penetration, In.	Location of Picture		Lattice Constant, Å.	Per Cent Zinc
		In.	Units		
A5	0.0054	+0.0040	+7.4	3.6116	1
A5	0.0054	0.0000	0.0	3.6818	32
A5	0.0054	-0.0020	-3.7	3.6905	35.5
A5	0.0054	-0.0040	-7.4	3.6940	37
A6	0.0094	+0.0075	+8.0	3.6098	0
A6	0.0094	+0.0055	+5.9	3.6144	2
A6	0.0094	+0.0025	+2.7	3.6651	25
A6	0.0094	0.0000	0.0	3.6802	31.5
A6	0.0094	-0.0030	-3.2	3.6878	34.5
A6	0.0094	-0.0065	-6.9	3.6946	37

TABLE 4.—*X-ray Data for Master Curve for Series B*

Sample No.	Total Penetration, In.	Location of Picture		Lattice Constant, Å.	Per Cent Zinc
		In.	Units		
B5	0.0048	+0.0040	+8.3	3.6147	2.5
B5	0.0048	+0.0028	+5.8	3.6201	5
B5	0.0048	+0.0008	+1.7	3.6612	23.5
B5	0.0048	-0.0004	-0.8	3.6799	32
B5	0.0048	-0.0020	-4.2	3.6850	33
B6	0.0098	+0.0083	+8.5	3.6096	0
B6	0.0098	+0.0060	+6.1	3.6192	4.5
B6	0.0098	+0.0051	+5.2	3.6364	13
B6	0.0098	+0.0041	+4.2	3.6492	18.5
B6	0.0098	+0.0025	+2.5	3.6585	22.5
B6	0.0098	0.0000	0.0	3.6742	29
B6	0.0098	-0.0020	-2.0	3.6808	31.5
B6	0.0098	-0.0038	-3.9	3.6874	34
B6	0.0098	-0.0057	-5.8	3.6893	35
B6	0.0098	-0.0082	-8.4	3.6934	36.5

TABLE 5.—*X-ray Data for Master Curve for Series C*

Sample No.	Total Penetration, In.	Location of Picture		Lattice Constant, Å.	Per Cent Zinc
		In.	Units		
C4	0.0048	+0.0045	+8.7	3.6111	0
C4	0.0048	+0.0020	+4.2	3.6558	21
C4	0.0048	0.0000	0.0	3.6786	31
C4	0.0048	-0.0020	-4.2	3.6870	34
C4	0.0048	-0.0035	-7.3	3.6897	35
C5	0.0069	+0.0055	+8.0	3.6122	1
C5	0.0069	+0.0035	+5.1	3.6370	13
C5	0.0069	+0.0010	+1.4	3.6600	23
C5	0.0069	-0.0005	-0.7	3.6759	29.5
C5	0.0069	-0.0030	-4.3	3.6844	33
C5	0.0069	-0.0055	-8.0	3.6889	35
C6	0.0086	+0.0060	+7.0	3.6170	3.5
C6	0.0086	+0.0035	+4.1	3.6449	17
C6	0.0086	+0.0015	+1.7	3.6630	24.5
C6	0.0086	-0.0005	-0.6	3.6751	29
C6	0.0086	-0.0025	-2.9	3.6829	32.5
C6	0.0086	-0.0045	-5.2	3.6876	34.5
C6	0.0086	-0.0070	-8.1	3.6897	35

units and the zinc content at the beginning of each unit was measured and replotted using units as abscissas, the curves for various times at any one temperature coincided. The curve resulting from this procedure is designated as the master curve in this paper. It was not possible to obtain enough X-ray data to determine the shape of the individual curves unless diffusion had continued long enough to produce a diffusion band at least 0.005 in. thick. Since this minimum diffusion band was not obtained

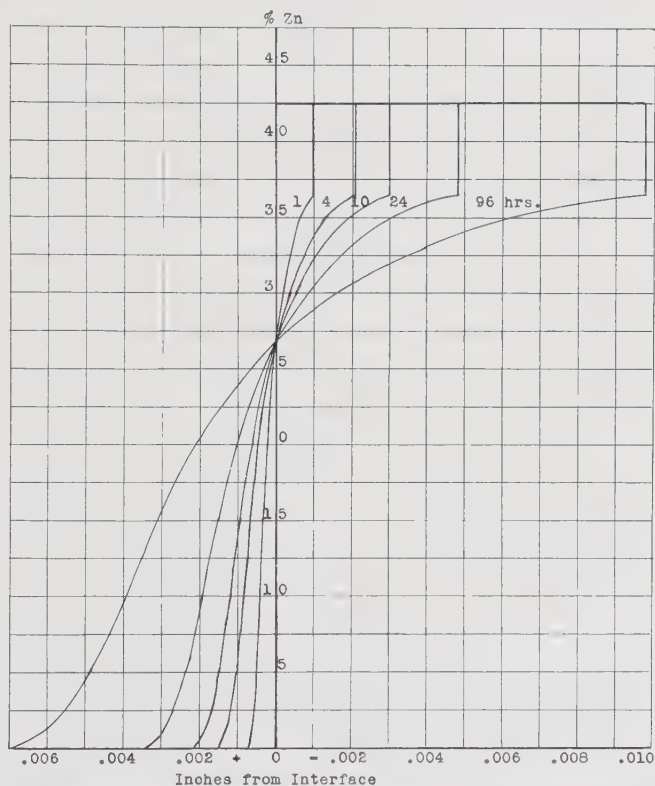


FIG. 17.—DIFFUSION CURVES FOR SERIES B. EFFECT OF TIME ON DIFFUSION AT 655°C.

for all samples, a master curve having units for abscissas was obtained as described above, using X-ray data for the samples having a distance between initial and final alpha-beta interfaces of 0.005 in. or more. Fig. 17, showing complete diffusion curves for samples having diffusion bands less than 0.005 in., was obtained from the master curve as described later.

Fig. 18 shows the master curve for the B series. Actually, to plot a point on this graph according to the method outlined above, the abscissa in units was obtained by measuring the distance of the surface used for the X-ray picture from the initial copper-brass interface, dividing this distance by the distance between the initial and final alpha-beta interfaces

for that sample (as obtained metallographically) and multiplying by 10. Since the X-rays penetrate to a considerable depth, the compositions as determined from the lattice constants were plotted as horizontal lines 0.001 in. long. The left-hand end of these lines gives the abscissas corresponding to the location of the surface for the X-ray picture. The following conditions were satisfied in drawing the master curves:

1. The areas on both sides of the interface were equal; i.e., an equal number of zinc and copper atoms exchanged places.
2. Both master curve and its first derivative were smooth.

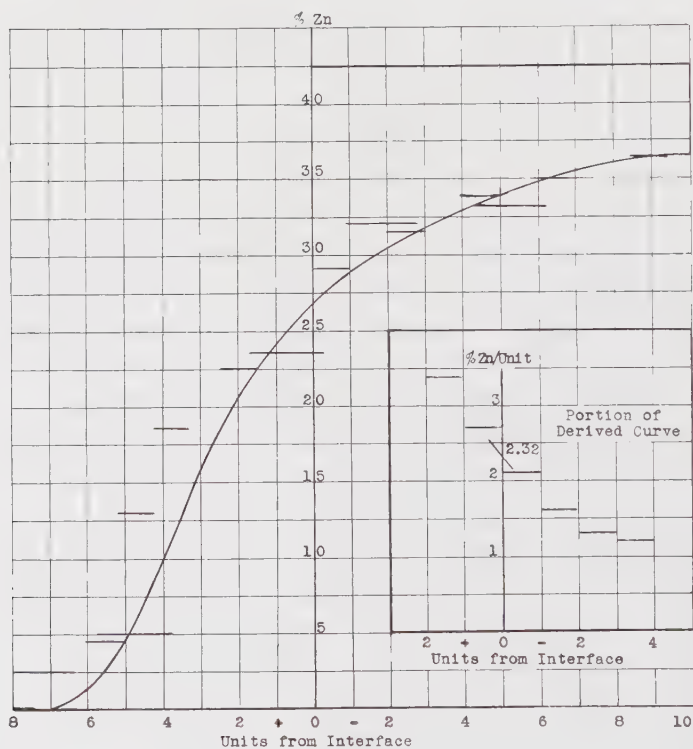


FIG. 18.—MASTER CURVE FOR SERIES B. SHAPE OF DIFFUSION CURVE AT 655°.

The master curves for all three of the series are shown together in Fig. 19.

The slopes of the master curves were obtained at the initial interface by plotting the derived curve in the vicinity of the interface (Fig. 18). This slope gave the concentration gradient when the units were changed to the corresponding number of inches for each sample. The factor for this conversion was 10 times the reciprocal of the distance from the initial to the final alpha-beta interface.

Fig. 17 was obtained by taking points from the master curve for series B and multiplying the abscissa by a factor. This factor was $\frac{1}{10}$ of the distance from the initial to the final alpha-beta interface. The amount of zinc, m , diffusing out of the beta brass may be found graphically from such curves as are found in Fig. 17. A square unit as obtained by this graphic integration and used later in the calculations is 2.5 per cent of the metal in a plate 1 sq. cm. in area and 0.001 in. thick.

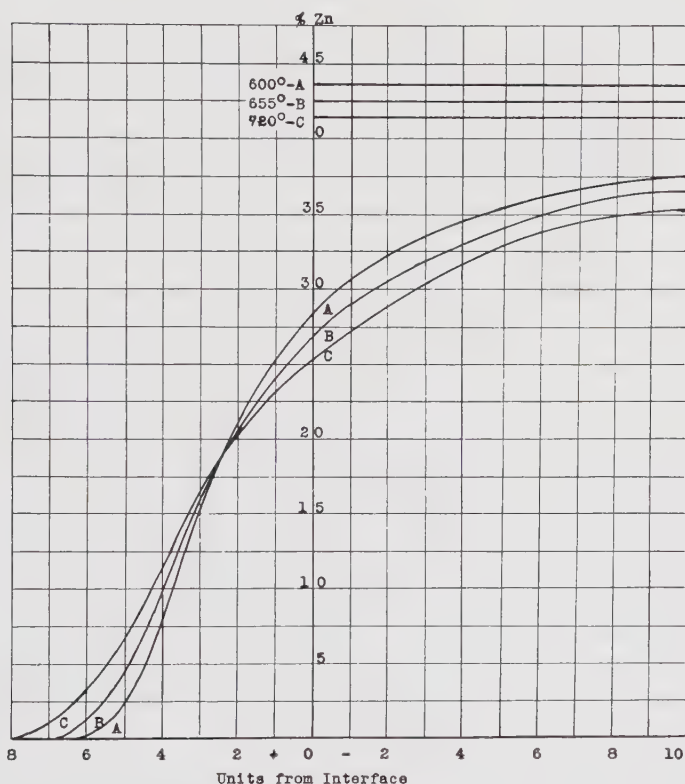


FIG. 19.—MASTER CURVES FOR SERIES A, B AND C. EFFECT OF TEMPERATURE ON SHAPE OF DIFFUSION CURVES.

The calculation of the diffusion coefficient was accomplished as follows: Rewriting Fick's law, and using unit area and small increments instead of differentials gives:

$$D = -\Delta m / (\text{mean } dc/dx) \Delta t \quad [2]$$

A simplified integration was carried out using five increments, with dc/dx known at the beginning of each increment. However, since a plot of m versus dc/dx was not linear, it would not be desirable to use an arithmetic mean. The mean dc/dx used was chosen so that in each

increment the same amount of metal diffused with a concentration gradient dc/dx greater than that chosen, as diffused with a concentration gradient dc/dx less than the mean chosen. The values for each of the

TABLE 6.—*Calculation of D for Series A*

	2 Hr.	9 Hr.	24 Hr.	96 Hr.	339 Hr.
m square units.....	3.24	6.48	10.80	19.4	33.8
dc/dx , per cent per 0.001 in.	29.65	14.83	8.90	4.94	2.84
Δm square units.....	3.24	4.32	8.6	14.4	
Mean dc/dx , per cent per 0.001 in.....	19.70	11.05	6.35	3.63	
Δt hr.....	7	15	72	243	
$D(10^{-11})$, sq. cm. per sec...	10.5	11.7	8.5	7.3	

TABLE 7.—*Calculation of D for Series B*

	1 Hr.	4 Hr.	10 Hr.	24 Hr.	96 Hr.
m square units.....	3.70	7.77	11.10	17.70	36.3
dc/dx , per cent per 0.001 in.	23.20	11.04	7.73	4.83	2.37
Δm square units.....	4.07	3.33	6.66	18.54	
Mean dc/dx , per cent per 0.001 in.....	15.0	8.95	5.95	3.25	
Δt hr.....	3	6	14	72	
$D(10^{-10})$, sq. cm. per sec...	4.1	2.4	3.6	3.6	

TABLE 8.—*Calculation of D for Series C*

	1 Hr.	3 Hr.	8 Hr.	16 Hr.	24 Hr.
m square units.....	6.08	10.64	18.24	26.22	32.67
dc/dx , per cent per 0.001 in.	12.50	7.14	4.17	2.90	2.32
Δm square units.....	4.56	7.60	7.98	6.45	
Mean dc/dx , per cent per 0.001 in.....	9.05	5.26	3.38	2.51	
Δt hr.....	2	5	8	8	
$D(10^{-9})$, sq. cm. per sec...	1.14	1.30	1.32	1.45	

quantities used in equation 2 as well as the calculated D 's for series A, B and C, are given in Tables 6, 7 and 8.

The four D 's for each temperature as obtained by equation 2 were then weighted according to the amount of metal diffused during the time that each was measured and averaged. These values are given in Table 9.

TABLE 9.—*Diffusion Coefficients for Various Temperatures*

Series	Temperature, Deg. C.	Diffusion Coefficient, Sq. Cm. per Sec.
A	600	8.6×10^{-11}
B	655	3.5×10^{-10}
C	720	1.3×10^{-9}

DISCUSSION OF RESULTS

Of the various equations used to calculate diffusion coefficients at different temperatures, the equation

$$D = Ae^{-Q/RT} \quad [3]$$

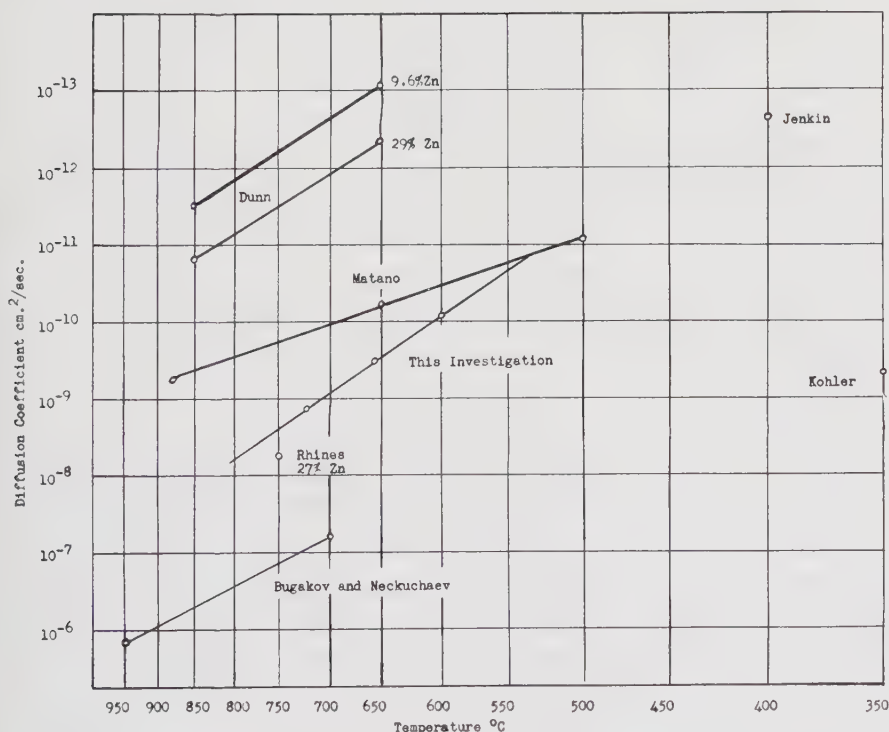


FIG. 20.—DIFFUSION COEFFICIENTS FOR ZINC IN ALPHA BRASS.

is probably the most commonly used. D is the diffusion coefficient, A is a constant, e is the base of the natural logarithms, Q is the heat of diffusion per gram atom, R is the gas constant and T is the absolute temperature. By expressing this equation in the form

$$\log D = \log A - (Q/RT) \log e \quad [4]$$

Q may easily be determined algebraically if the value of D is known at

each of two temperatures, or Q may be determined graphically by plotting the logarithm of D against $1/T$ and finding the slope of the resulting straight line. Q really expresses the effect of temperature on the rate of diffusion, and often is given along with the diffusion coefficients.

Fig. 20 is a plot of $\log D$ versus $1/T$. The various published values of D are shown on this plot as well as the results of this investigation. The wide variation in results is apparent. In most cases, sufficient information concerning the experimental procedure has not been published to make it possible to make a definite comment on the reason for these discrepancies. While one would not expect the data to fall on a single diagonal straight line, inasmuch as D varies considerably with the concentration of the alpha brasses used, the wide discrepancy is probably due not so much to the different brasses used as it is to the assumption made by some investigators in order to facilitate their calculations that D does not vary with concentration. In the author's work, Fick's fundamental diffusion law was used. Calculations were based on the composition of the brass at the original interface, which was constant.

Using equation 3 and the data in Table 9, Q may be calculated and is found to be 39,100 cal. per gram atom.

This value for Q , which can also be obtained from the slope of the lines in Fig. 20, is very close to that of Dunn's work as well as Bugakov and Neskuchaev's work. In other words, while the diffusion coefficients are different, they show the same variation with temperature. Rhines' work^{4,5} gives a value for the diffusion coefficient very close to that of the authors' (Fig. 20).*

The complete Dushman-Langmuir equation:

$$D = (Q/Nh)\delta^2 e^{-Q/RT} \quad [5]$$

requires only one value of D for its solution. N is the Avogadro number, h is Planck's constant and δ is the interatomic distance. Although several experimenters have doubted its veracity, it is possible that lack of accurate measurements may account for this skepticism. Using the data of Table 9 and a δ of 2.61×10^{-8} cm., Q will be found to have the following values:

$Q = 38,000$ cal. per gram atom at 600° C.; $37,700$ at 655° C., and $37,800$ at 720° C.

The agreement between the value for Q as obtained by the Dushman-Langmuir equation (about 38,000 cal. per gram atom) and the more generally accepted equation 3 (about 39,000 cal. per gram atom) is very good.

* Rhines' work was published in part in 1937 and later in full subsequent to the completion of the present work.

SUMMARY

The purpose of this investigation was to determine the rate of diffusion of zinc and copper in alpha brass, and to ascertain the effect of temperature on the rate of diffusion.

Three diffusion coefficients have been determined at three different temperatures on substantially the same alpha brass. From these results it is possible to calculate the probable rate of diffusion in this alpha brass at any temperature below its melting point, by means of either of two equations cited in this paper.

The method used has made it possible to eliminate any uncertainties concerning the variation of rates of diffusion with concentration as well as those concerning the superficial area of a porous surface, factors that have entered into earlier investigations.

The coefficients of diffusion as determined in this investigation are given in Table 10. These rates of diffusion have been shown to fit the

TABLE 10.—*Coefficients Determined in This Investigation*

Diffusion Coefficient, Sq. Cm. per Sec.	Temperature, Deg. C.	Composition of Brass, Weight Per Cent Zinc
8.6×10^{-11}	600	28.3
3.54×10^{-10}	655	26.8
1.31×10^{-9}	720	25.3

generally accepted equation

$$D = Ae^{-Q/RT}$$

which shows the effect of temperature on diffusion. The value of Q in this equation has been found to be 39,000 cal. per gram atom, from the results listed.

The substitution of any one of the diffusion coefficients from Table 10 in the less empirical equation

$$D = (Q/Nh)\delta^2e^{-Q/RT}$$

gives a value for Q of about 38,000 cal. per gram atom, which is in exceptional agreement with the value of Q just mentioned.

REFERENCES

1. C. H. Desch: Report on Diffusion in Solids. *Repts. Brit. Assn. for Advancement Sci.* (1912) **82**, 348-372.
2. R. F. Mehl: Diffusion in Solid Metals. *Trans. A.I.M.E.* (1936) **122**, 11-56.
3. A. I. Krynsky: Diffusion in Solid Metals, I, II and III. *Metals and Alloys* (1937) **8**, 138-144, 173-179, and 261.
4. R. F. Mehl: Rates of Diffusion in Solid Alloys. *Jnl. Applied Physics* (1937) **8**, 174-185. (Includes some results by F. N. Rhines.)

5. F. N. Rhines and R. F. Mehl: Rates of Diffusion in the Alpha Solid Solutions of Copper. *Trans. A.I.M.E.* (1938) **128**, 185.
6. Bugakov and Neskuchaev: A Method for the Investigation of the Diffusion Coefficients of Metals by Means of Evaporation. *Tech. Phys. U. S. S. R.* (1934) **1**, 329-334.
7. J. S. Dunn: Diffusion of Zinc in Alpha Series of Solid Solutions in Copper. *Jnl. Chem. Soc.* (1926) **129**, 2973-2979.
8. W. Kohler: Diffusion of Zinc in Copper and Copper-Zinc Mixed Crystals at 350°—Diffusion in the Solid State. *Zentr. Hutten Walzwerke* (1928) **31**, 650.
9. C. H. Desch: Diffusion in Solids. *Int. Crit. Tables* (1926) **5**, 77. (Includes some results by Jenkin.)
10. C. Matano: X-ray Studies on the Diffusion of Metals in Copper. *Japan. Jnl. Physics* (1934) **9**, 41-47.

